Three-Dimensional Vectorial Time-Domain Computational Photonics

Customers with requirements for secure data transmission, computer networking, and high-bandwidth instrumentation are accentuating the need for photonic integrated circuit (PIC) technology. PICs will be the high-speed processing chips of the future and will impact both commercial and LLNL programmatic needs. Compact (LSI to VLSI), low-latency (sub-ps), wide-bandwidth (THz), ultrafast (100 Gb/s) miniaturized digital-logic, transmission, and sensor systems are potentially feasible. The design of novel integrated structures poses a considerable challenge, requiring models incorporating both microscopic and macroscopic physics.

Despite the strong photonic modeling capability at LLNL, new numerical methods are necessary as more complex photonic devices, materials, and configurations are devised. We are doing the research necessary to create these new numerical methods.

Project Goals

We are filling the gap between existing modeling tools and those needed for LLNL programs by extending the state of the art in simulation for the design of 3-D PICs. We have defined challenges that must be addressed in our codes, such as models for optical gain and nonlinearities, as well as microscopic, nonuniform, inhomogeneous structures. Our tools leverage LLNL's expertise in computational electromagnetics and photonics.

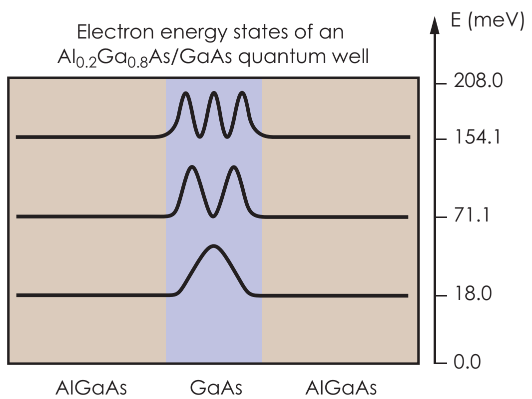
We are developing models and algorithms for incorporation into a new generation of 3-D simulation tools. These tools will be general enough to be adapted to problems in many areas, and flexible enough to embrace the design of future mixed-signal systems as well as stand-alone systems in disparate regions of the EM spectrum.

Relevance to LLNL Mission

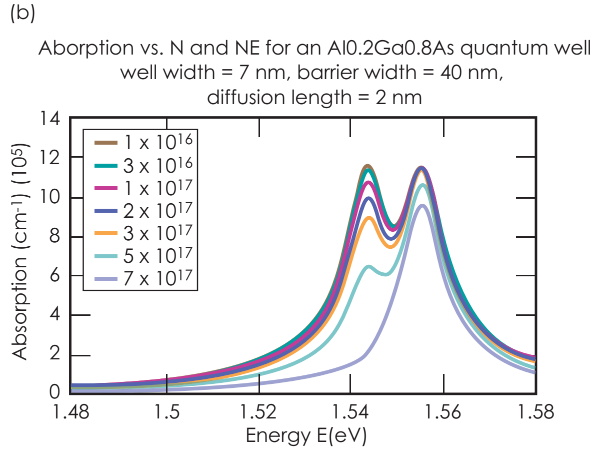
The ability to model complex 3-D photonic devices in the time domain is essential to LLNL for a broad range of applications. These include: high-bandwidth instrumentation for NIF diagnostics; microsensors for weapon miniaturization within the DNT programs; encryption devices and circuits for secure communications for NAI surveillance applications; high-

Figure 1. (a) Electron wave functions for a 70-Å wide quantum well. (b) Absorption due to the quantum well as a function of photon energy and carrier density. The absorption can be converted to an index of refraction through the Kramers-Kronig relations.

(a)



(b)



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density optical interconnects for high-performance computing; and detection devices for homeland security.

FY2005 Accomplishments and Results

Most of our work has been focused on extending our two research codes: Quench3D and EMSolve. Quench3D is a narrow-bandwidth scalar beam-propagation-method code built for modeling large devices in which light propagates in a preferred direction. EMSolve is a vector time-domain code used for modeling small devices with either complicated geometries and/or no preferred direction for propagation.

In the past year we have:

1. written a vector finite-element beam-propagation solver for incorporation into the Quench3D suite;
2. written a significantly faster matrixless solver for EMSolve (which will speed simulation of materials with time-varying constitutive parameters);
3. incorporated new finite-element operators (wedge products) into EMSolve;
4. incorporated a drift diffusion model for carriers (electron-hole pairs) into EMSolve; and
5. written software to extract constitutive parameters for quantum well materials as a function of carrier density (Fig. 1).

We have been using the results of this work to examine designs for Auston-Switch Terahertz (THz) sources (Fig. 2), examine the effects of operating phased arrays of Auston Switches, and simulate the time course of electron-hole carrier diffusion in bulk semiconductor material.

Related References

1. Bond, T. C., and J. S. Kallman, "Time-Domain Tools for the Investigation of Gain-Quenched Laser Logic," *International Semiconductor Device Research Symposium*, Washington, DC, December 10-12, 2003.

2. Koning, J. M., D. A. White, R. N. Rieben, and M. L. Stowell, "EMSolve: A Three-Dimensional Time Domain Electromagnetic Solver," *Fifth Biennial Tri-Lab Engineering Conference*, Albuquerque, New Mexico, October 21-23, 2003.

FY2006 Proposed Work

Next year's work will consist of developing and incorporating gain and spontaneous emission algorithms into the EMSolve code, and replacing Quench3D's scalar beam-propagation solver with a wide angle vector finite-element beam-propagation solver. The upgrade to EMSolve will allow us to model optically-driven THz sources and Vertical Cavity Surface Emitting Lasers (VCSELs). The upgrade to Quench3D will allow us to examine the polarization dependence of the light emitted from semiconductor lasers, as well as that of gain-quenched laser logic. We will continue modeling devices for a variety of program-related projects.

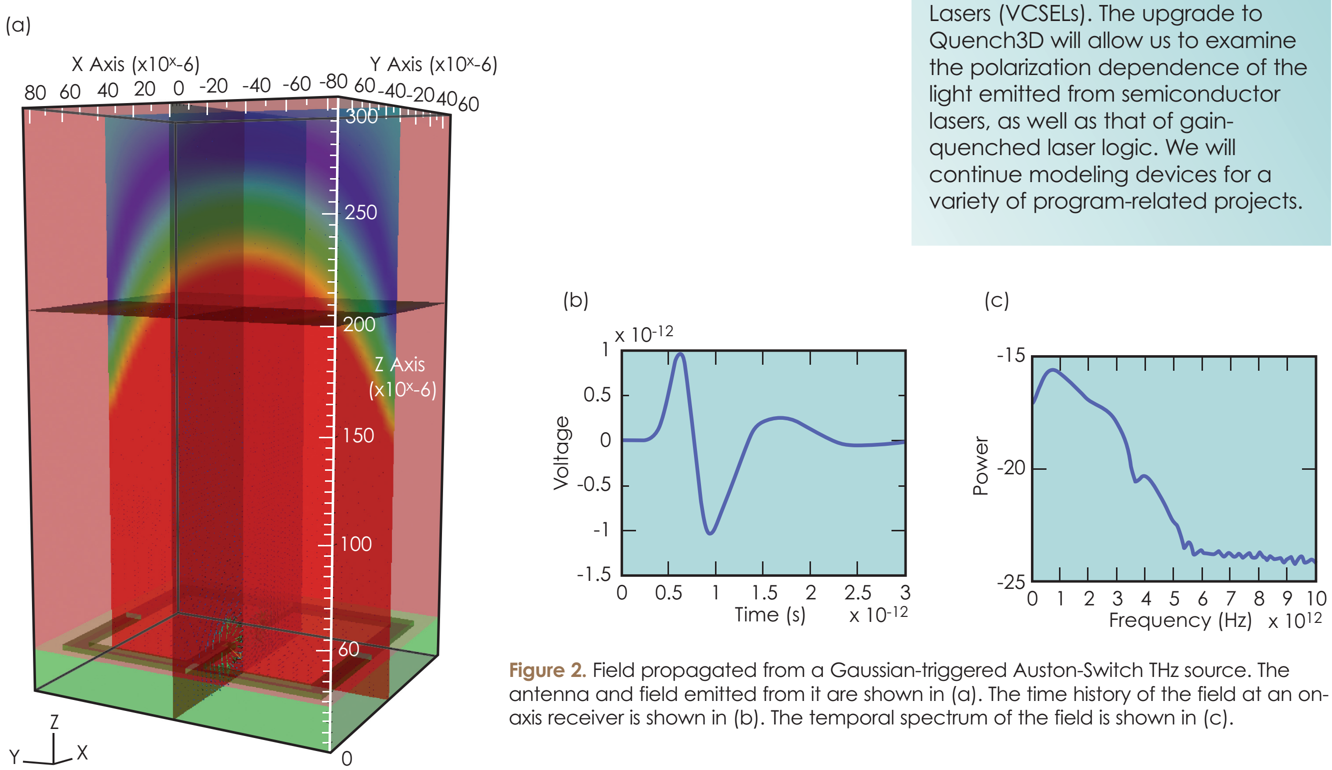

Figure 2. Field propagated from a Gaussian-triggered Auston-Switch THz source. The antenna and field emitted from it are shown in (a). The time history of the field at an on-axis receiver is shown in (b). The temporal spectrum of the field is shown in (c).